Planning sensor locations for the detection of radioactive plumes for Norway and the Balkans[1]

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Abstract: Locations of gamma dose rate sensors have often been chosen by administrative or geometrical criteria. Nowadays computational capacity allows for a more realistic basis. We use simulations of potential radioactive plumes based on weather data of one year to investigate the threats to regions without own nuclear power plants and to find good numbers and locations of sensors to detect such plumes. We base optimisation a cost function that can take into account numbers of undetected plumes, their dose to the region in general, or on the population. Besides we assess the effect of administrative constraints, be it that sensors have to cover administrative units, or that optimisation is done for sub-regions separately. Finally we evaluate the robustness of the approach. The main findings are that sensors at boundaries are often best, but also typical paths of plumes may be important, and that administrative constraints may necessitate much higher numbers of sensors. The small numbers of sensors actually deployed in these regions seem sufficient. However, the latter may be an artefact of the low number of plumes we considered. Altogether, combined with other considerations, this approach can contribute to better decisions about gamma dose rate sensor locations.

1 INTRODUCTION

In this study we investigate where radioactive plumes from abroad are likely to pass and where sensors should be located to detect them. Starting from scratch we add sensors until all considered plumes can be detected or until a desired number of sensors is reached. This is based on simulated plumes from several nuclear power plants in neighbour countries of the region of interest. The weather data for the simulations is derived from reanalysis data for a full year. For more simple simulations, there has been research on multi-objective optimisation of sensor locations [1]. Adapting existing monitoring networks was treated in an earlier publication [2].

Norway and the Balkans (Albania, Bosnia, Croatia, Kosovo, Macedonia, Montenegro, Serbia) are typical regions without own commercial nuclear power

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plants but threats from abroad. In both regions rather sparse sensor networks are run, which are mainly meant for detection of radioactive plumes and to trigger more monitoring in emergencies. The main focus is on Norway, the Balkans serve for comparison and also to test the effect of national versus international optimisation.

2 METHODS AND DATA

2.1 Plume simulations

The plume simulations for this study are made with the RIMPUFF dispersion model [3, 4]. The input meteorological data with one hour resolution is calculated with the Weather Research and Forecast Model [5], based on NCEP reanalysis data [6, 7]. During all of 2007 a new twelve hour release is started every 84 h and simulated for up to seven days. The nuclide vector consists of Kr-88, Sr-91, I-131, Xe-133, Xe-135, and Cs-137 at a constant release rate of $1 \cdot 10^{12}$ Bq/s for each nuclide, released as puffs every 30 min. Release height is 50 m and no heat is considered. The releases are started at locations of nuclear power plants possibly threatening the regions of interest, these are Chernavoda (RO), Kozloduy (BG), Krsko (SI), Paks (HU), and Temelin (CZ) for the Balkans; Forsmark (SE), Kola (RU), Ringhals (SE), Torness (UK), and another source close to Andoya (15.5°E, 69.5°N), to take into account threats from nuclear powered navy vessels, for Norway. The resulting dose rates are computed at a grid with 4 km resolution.

2.2 Cost functions and optimisation

The aim of the optimisation is to minimise the cost function that assigns a value to each given set of sensors. The cost function is based on the simulated plumes. For each plume $i \in I$, for all time intervals $t \in T$ and locations (grid cells) $x \in X$, the gamma dose rate $r_i(x,t)$ is known from the simulations. We only care, if a plume could be detected at a location at all during the whole plume passage. The detection threshold is set to 100nSv/h based on different national limits for early warning in Europe. Therefore the following indicator function (1) is used

$$K(i,x) = \begin{cases} 1 & \text{if } \forall t \in T: r_i(x,t) \leq 100\,nSv/h \\ 0 & \text{else (i.e. if plume } i \text{ is detected at location } x) \end{cases} \tag{1}$$

For a set of sensors $S = \{x_1, \ldots, x_m\} \subseteq X$, the cost (2) is the (weighted) number of plumes that are not detected by any of the sensors

$$c(S) = \sum_{i \in I} w(i) \cdot \prod_{x_j \in S} K(i, x_j) \tag{2}$$

For Norway we apply three different weights, the simplest is the number of undetected plumes $w_{\text{number}}(i) \equiv 1$ for c_{number}. However, some plumes cause much higher doses in the area of interest or to the population than others. To focus on the most important ones, we also use the total dose of the plume to the

area of interest $w_{area}(i)=\sum_{x\in X}\sum_{t\in T} r_i(x,t)$ for C_{area} and the total dose of the plume to the population in this area $w_{population}(i)=\sum_{x\in X} p(x)\sum_{t\in T} r_i(x,t)$ for $C_{population}$ where $p(x)$ is the population in the grid cell $x\in X$. The Norwegian population is derived from a map of all settlements with more than 200 inhabitants [9] assuming equal distribution of the remaining 21% of the population. For the Balkans, only C_{number} is used.

The optimisation algorithm is greedy one-by-one search. All grid cells are considered possible sensor locations. First the sensors are added one-by-one: to find the best next sensor location, we compute for each location the cost if an additional sensor would be placed here. Always the best sensor is added –if there are several, we take the most south-western one– and the whole step is repeated. Then all redundant sensors are deleted, to find the smallest set of sensors that still can detect all considered plumes. If required, we continue deleting sensors, removing always the least important one, until the desired number of sensors is reached. Deleting some of the sensors can also avoid overfitting as it will first remove the sensors that are only needed for exclusive detection of single plumes. Here the desired numbers of sensors were 19 for Norway and 16 for the Balkans. These correspond to similar sensor densities and in Norway this fits the number of administrative units. Figure 1 shows how C_{number} changes during optimisation.

Often locations of gamma dose sensors have to fulfil **political constraints**. A typical request is that each administrative unit has at least one sensor. We optimised sensors for Norway under this constraint for the 19 administrative units (“fylke”). When adding sensors, each has to be placed in a different “fylke” until there is one in each. When deleting sensors, it is not allowed to take the last sensor from a “fylke”. Another political issue is, if agencies of neighbouring countries trust each other, or if each one wants to run enough sensors itself to be independent. The effect of both strategies was investigated for the Balkans, where optimisation was run for the whole region, and then for six sub-regions separately using only plumes that are detectable in the respective sub-regions.

The optimisation result may be very **sensitive** towards the set of plumes considered. Therefore we run the optimisation with less plumes to determine if the sensors would also detect the plumes not considered for their optimisation and how much the locations would change. We either skipped the plumes regularly or we omitted all plumes from one of the sources.

All computations, except plume simulation, were carried out with the statistical programming language R [8].

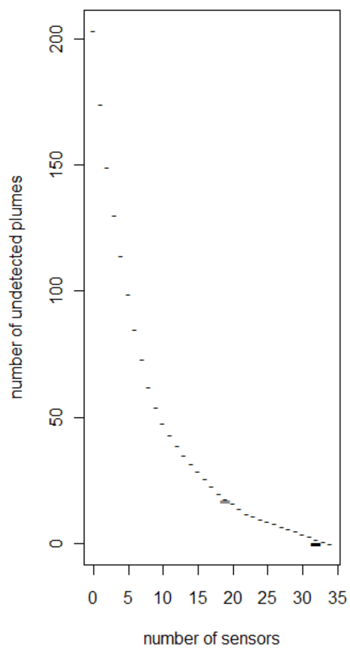


Figure 1. C_{number} for Norway; black –sensors added one-by-one; bold black –redundant sensors deleted; bold grey –final

3 RESULTS

3.1 Properties of the plumes

Table 1. Fraction of the area of interest covered by the single plumes. Numerator and denominator are

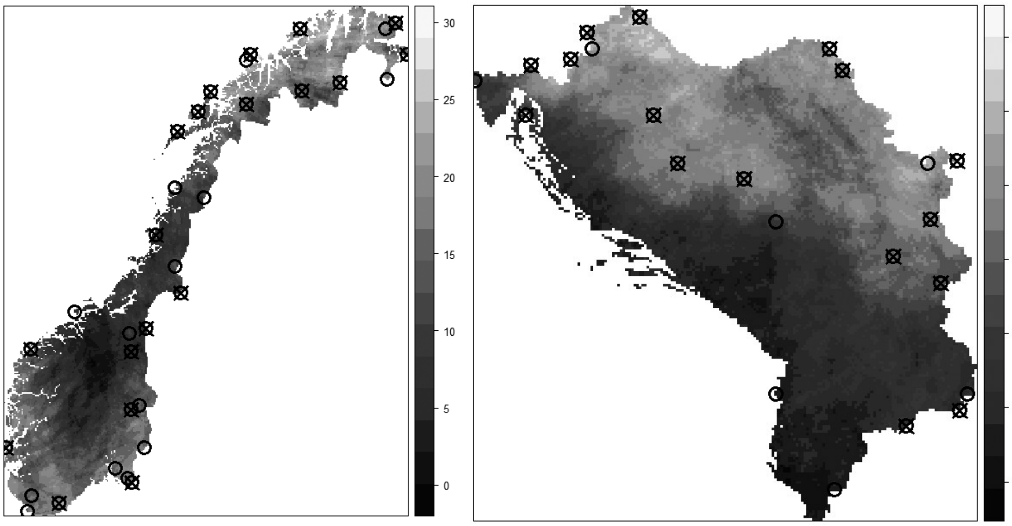
	min	*median*	*max*	*mean*
Norway	1/20255	831/20255	7203/20255	0.061
Balkans	1/16817	1140/16817	10040/16817	0.116

From the 104 simulated plumes from each source, many never reach the region of interest. Of the 520 plumes from the five sources considered in both use cases respectively, only 203 for Norway and 295 for the Balkans can be used for the optimisation. Most plumes are small, Table 1 shows statistics on how much of the area is covered by one plume. For Norway there are three plumes only detectable in one cell, for the Balkans there are two. The plumes in Norway are smaller and the area of interest is bigger, therefore on average the fraction covered by each plume is only about half compared to the Balkans.

3.2 Optimal sensor locations for detection

The minimal number of sensors to detect all plumes for Norway is 32, whereas for the Balkans 23 sensors are sufficient even if more plumes are considered there. The best 19 sensors for Norway miss 17 of the plumes, the best 16

Figure 2. Optimal sensor locations for Norway (left) and the Balkans (right). All of the considered plumes are detected from the sensors at O . If only19 or 16 sensors respectively are used, the optimum are the ones at ⊗ . Background: number of plumes



sensors for the Balkans only miss seven. As described above, the plumes at the Balkans overlap more and can therefore be detected with less sensors. Figure 2 shows maps of the optimal sensor locations. In Norway, sensors should be placed at the coasts and borders. For the Balkans borders are as well important sensor locations, whereas no plumes threaten the region from the coast, but there seems to be a main path of plumes in the centre of the region where sensors should be placed. In both cases the most important 19 or 16 sensors respectively (⊗) are more spread than the other ones (O). However, also these are clustered close to sources like the marine Andoya source for Norway and the nuclear power plant Krsko for the Balkans.

3.3 Optimisation for low dose

The the sensor locations resulting from optimisation with C_{area} and $C_{population}$ for Norway differ from those for C_{number}. Also

	C_{num}	C_{are}	C_{popula}
optimised for	17	0.14	63.6
optimised for	21	0.03	16.0
optimised for	22	0.08	13.9
existing	49	1.24	209.0

the number of sensors needed to detect all

Table 2. Cost for sampling designs of 19 sensors optimised for different cost functions and for the

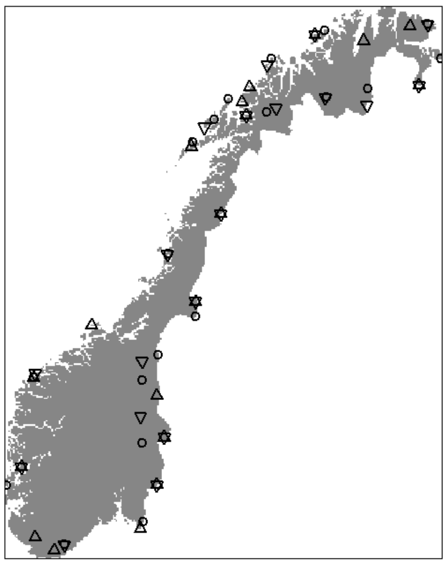


Figure 3. The 19 best sensors for the cost functions C_{number}(O), C_{area}(∇), $C_{population}$(

plumes is higher: 34 and 36 sensors for $C_{\text{population}}$ and C_{area} respectively. These results are obviously worse than the one from C_{number} where only 32 sensors are needed for the same detection capability. However, if less sensors are used, those optimised for one cost function always perform best in this respect, see table 2.

3.4 Administrative constraints

On the one hand the constraint, that each “fylke” must have at least one sensor, considerably impairs the result for Norway. The first four sensors can be located as before, but for further sensors the constraint only allows suboptimal locations. Altogether 38 sensors are needed to detect all plumes and the 19 best ones leave 56 plumes undetected. Thus about six more sensors than else are needed. On the other hand the sensors optimised without this constraint are very far from meeting it: the 19 best sensors are located in only ten of the “fylke”.

Optimising sampling designs for sub-regions of the Balkans clearly showed that much more sensors are needed if each sub-region wants to be independent, see figure 4. For the latter, 75 sensors are necessary, whereas for joint sampling 23 sensors are sufficient. 13 of the sensors are the same in both cases, mainly in Croatia where most plumes come from the nuclear power plant Krsko very close to the border.

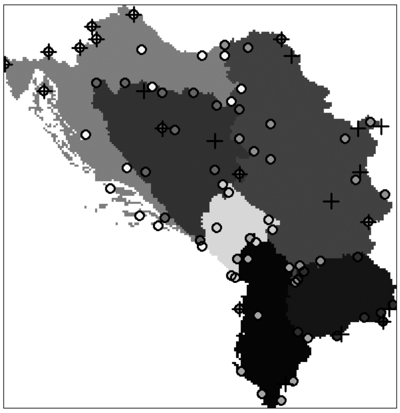


Figure 4. Sampling designs detecting all plumes: O sensors optimised for the subregions separately; + sensors optimised for the

3.5 Robustness

The set of simulated plumes can never cover all possible plumes that may ever occur. We tested the sensitivity of the results by running the whole optimisation on reduced sets of sensors. First we excluded regularly 1/20, 1/10, 1/4, or 1/2 of the plumes respectively. Second we excluded all 75 plumes from one source (Andoya) or a random set of 75 plumes. In each case we determined the full sampling design that can detect all of the remaining plumes and the 19 most important sensors. As described in table 3, the number of sensors needed to detect all plumes grows with the number of these plumes. As expected, only some of the plumes not considered in the optimisation are detected by chance, on average about 3/4 are still detected. This fraction is worse if complete sources are ignored. But from a different point of view, the 19 best sensors

Table 3. Results from optimisation with less plumes.

whereas when plumes from Andoya are considered, the 19 best sensors miss 1 plume from Andoya and 16 else.

mean numbers of	plumes sensors	all (203)	regular 95% (193)	 90% (183)	 75% (153)	 50% (102)	random (128)	one source (128)
sensors	all	32	30.6	29.5	27.8	22	26	24
undetected	all	0	2.1	4.1	11	25	14.6	26

plumes	19	17	17.9	18.2	24	30	26.8	34
sensors	all	all	21.4	19.6	15	10	12.2	12
coinciding with original	19	19	9.2	9.4	7	6	4.8	4

The sensor locations themselves also depend a lot on the set of plumes considered. From the full set of sensors between 9 and 27 coincide with the original ones. The differences for the sampling designs of 19 sensors are even bigger. Also among the sets of sensors, there are big differences, one location occurs in 39 of the 43 full sets, but the median occurrence is two. In general the differences are biggest if few plumes have been used. These results show that the sensor locations are very sensitive to the input and probably more simulated plumes are needed to give realistic results.

4 DISCUSSION

The optimisation algorithm used here is fast and only tries very few possible combinations of e.g. 19 sensors within Norway. Therefore there is no guarantee, that it will find the global optimum. For one case we run a more extended search and found sets of 19 sensors that could detect one more plume. This shows that the algorithm used here did not find the global optimum but was close.

However, the most critical issue seems to be the number of plumes used, but running simulations with less temporal distance may lead to high correlations. Therefore finding a good set of plumes remains a challenge.

5 CONCLUSIONS

We built an algorithm that allows integrating climatic data into the search for locations for gamma dose rate sensors in regions where threats mainly come from abroad. In our use cases, the best locations for sensors were mainly at boundaries and coasts but also highly affected regions within the areas of interest could be identified. This algorithm also allows focussing on plumes severely affecting the area of interest or the population, yielding intuitive results like more sensors in densely populated areas. We also assessed the price of political decisions like national instead of international monitoring. On the Balkans the former would need more than three times as many sensors to achieve the same detection capability. In general the results showed, that few sensors (about 1 per 15 000 km^2) were sufficient to detect many of the plumes. However, we also observed that probably more plumes should be used as about one quarter of the not considered ones pass undetected. To avoid overfitting, only locations where several plumes can be detected should be chosen. Altogether this algorithm can contribute substantially to improve decisions about gamma dose rate sensor locations, but it should be combined with other approaches. As the quality of a sampling design for this respect can be quantified with the cost function it can easily be combined with other quantitative criteria.

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